



Sandia  
National  
Laboratories

CENTER 5200

# Advanced quantum sensing technologies & underground utility detection



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*ARPA-E Undergrounding Workshop, 19 July 2022*

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- Overview of current underground sensing technologies from geophysics
  - EMI, GPR, passive magnetic, etc.
- Topside vs. down-hole sensing considerations
- Quantum sensing modalities for underground detection:
  - RF magnetometry
  - Gravimetry
- Recent progress in sensor development at Sandia

# Geophysical interrogation of the urban subsurface – a Maxwell perspective



**Strategy:** Correlate anomalies in electromagnetic material properties (susceptibility, conductivity, permittivity) with the presence of anthropogenic artifacts (pipes, rebar, etc.) or naturally occurring heterogeneities such as voids or bedrock variability.

**Challenges:** tradeoff between depth sensitivity and signal fidelity; ambient background noise overwhelming subtle signals of interest; false positives; cumbersome data collects, non-uniqueness.

## Electromagnetic Spectrum

Electro/Magneto-statics

Freq = DC

Depth ~100s m

mHz

Time- or frequency-domain induction

Hz

10s m

kHz

MHz

Ground Penetrating Radar

1-10 m

GHz

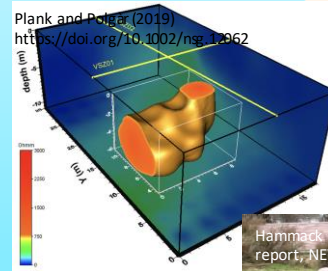


1

- Deploy an array of electrodes on/in ground
- Energize various pairs as “sources” while measuring voltage differences between remaining pairs

Imaging karst voids with DC voltages

Plank and Polgar (2019)  
<https://doi.org/10.1002/nag.1862>



2

Broadband EM uses a time-varying source signal that can be either direct or inductively coupled to the ground

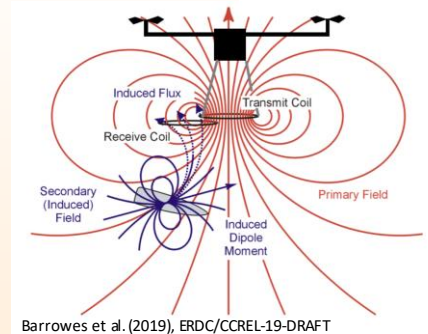
3

Data can be electrode voltages and/or magnetic field fluxes. Various combinations are available.

COTS GPR and EM Induction Sensors

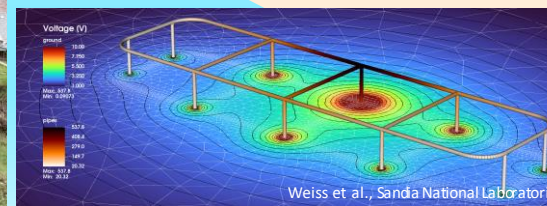


Prototype UAV packages



Barrowes et al. (2019), ERDC/CCREL-19-DRAFT

Direct excitation of pipe assemblages

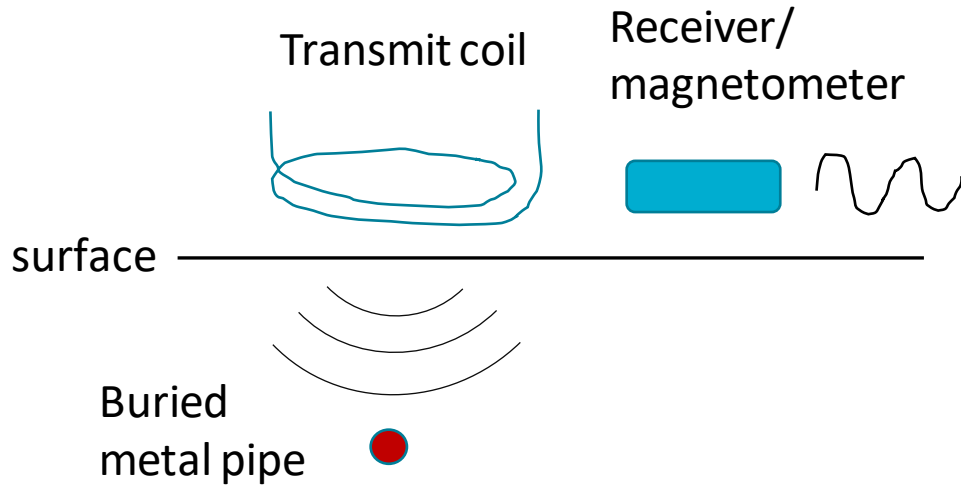


Needs and Opportunities

- Real-time data integration/analysis/visualization
- Physics-informed ML for multi-modal data (seismic + EM?) data reduction.
- Exploitation of “noise” for better resolution
- Optimization for drone/other data collect platforms

Magnetic Prospecting for Abandoned Wells

# Electromagnetic induction (EMI)



## Faraday's Law

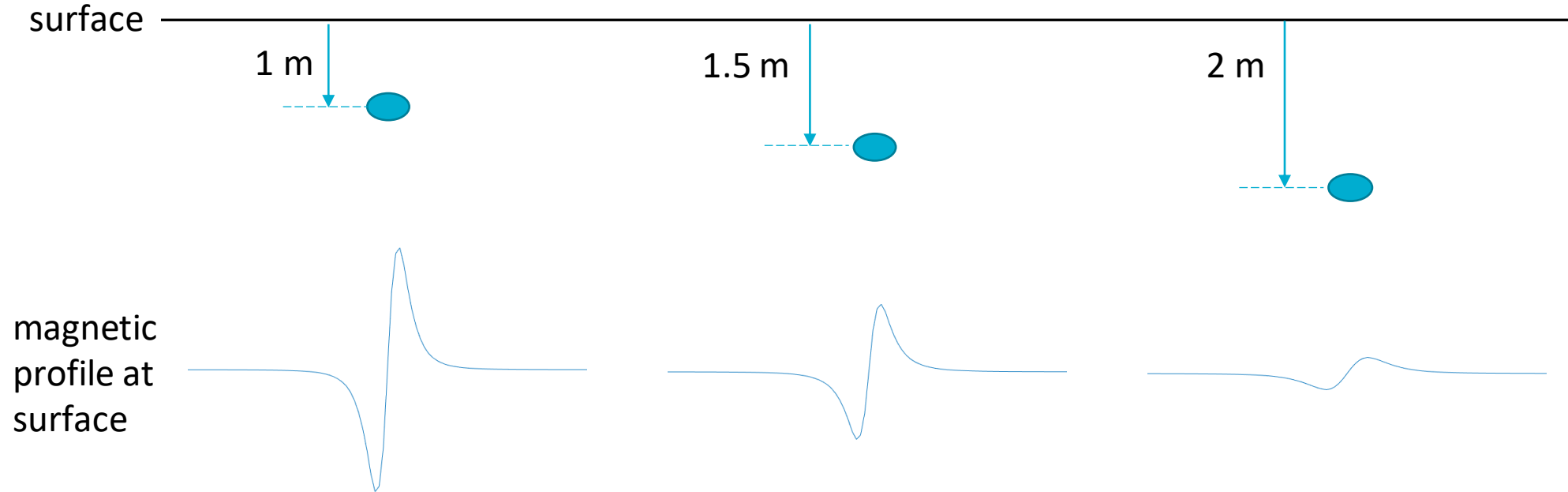
$$V_{ind} = - \frac{d\Phi_B}{dt}$$

$$\Phi_B = \oint_S \vec{B} \cdot d\vec{A}$$

- EMI = active technique to detect conductors by inducing current in buried object via Faraday's Law.
  - Time and frequency domain methods
- Advantage: works for all metals, ferrous or non-ferrous (aluminum, copper, etc.)
- Disadvantage: Range and detection swath are limited by physics of transmission and reception of induced magnetic field.
- $1/R^6$  range dependence of signal when  $R \gg d$  ( $d$ =transmit coil diameter).
- Additional loss of signal due to attenuation in soil
  - Skin depth  $\propto 1/\sqrt{f}$
  - Low frequency penetrates deeper
  - $f = 50\text{-}480$  kHz (tune for depth)
- EMI commonly used to detect buried cables, pipes at  $>2$  m depth (up to 10 m) with reduced spatial resolution in horizontal plane

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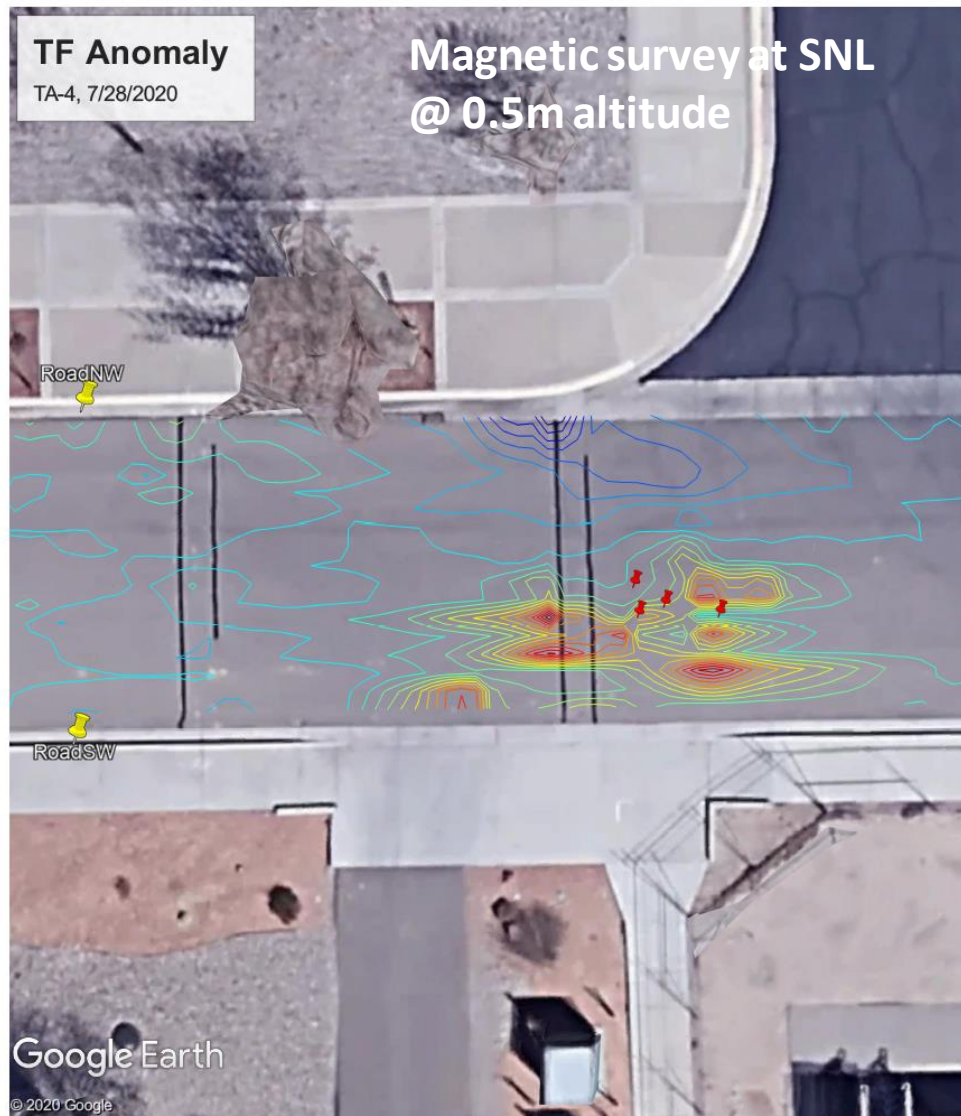
# Depth dependence of magnetic signature (dipole)



- Amplitude decreases *nonlinearly* with depth ( $1/R^3$  for dipole,  $1/R$  for cable)
- Width of profile is *proportional* to depth



# Passive magnetic sensing



- Passive magnetic sensing relies on magnetism of the buried object
- Advantage: Greater detection depth
  - $1/R^3$  range dependence of signal for dipole source
  - No loss from soil attenuation
- Disadvantages:
  - Only works for iron-containing (ferrous) metals
  - Signal can be confused by nearby surface magnetic objects (clutter).
- Greater detection depth is possible than with EMI, but with low spatial resolution due to spreading effect of dipole fields

**Geometrics magnetic survey**



**Horizontal drilling**

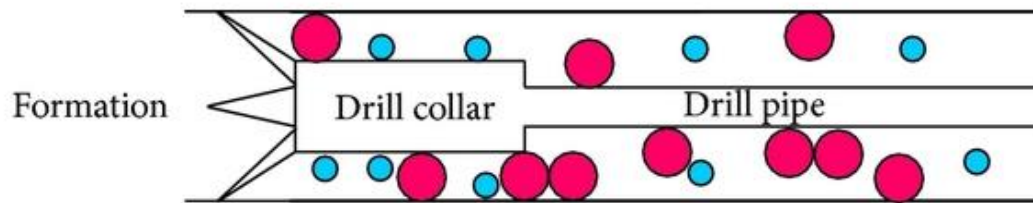


Photo licensed under Creative Commons 3.0: [CC BY](#)

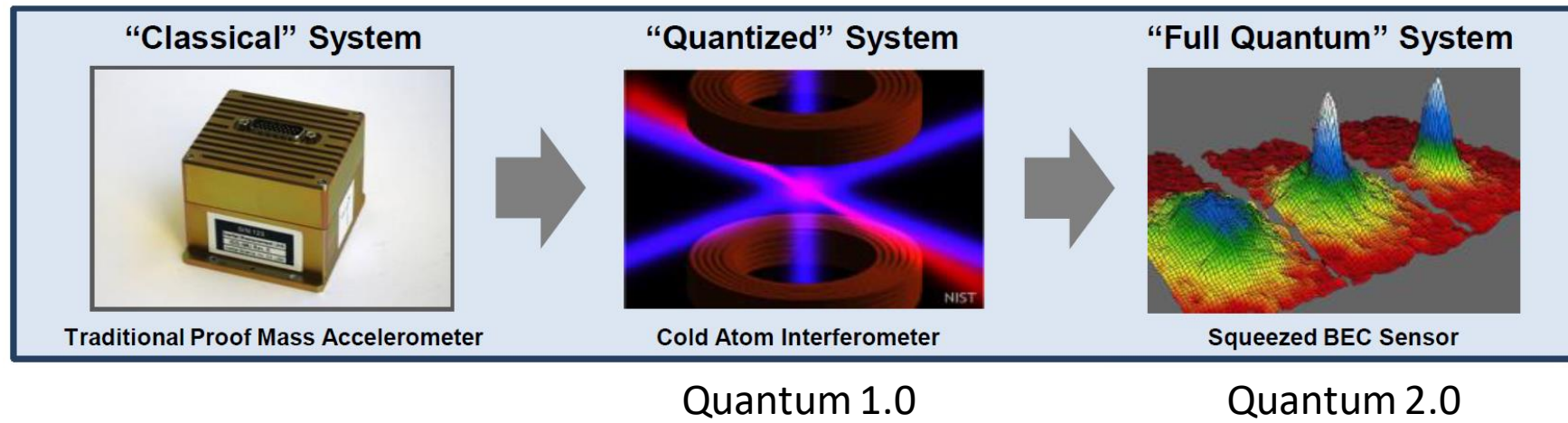
- Topside sensors can have higher SWaP and lower TRL
- Data collection includes GPS position
- Facilitates mapping
- Down-hole sensors are highly size-constrained (3-4 inch pipe ID)
- Rugged against shock & vibe, drilling mud
- No GPS data – better for obstacle avoidance than mapping
- Goal: prevent cross-bore events!

# What is quantum sensing?



1. Use of a quantum object to measure a physical quantity (classical or quantum). The quantum object is characterized by quantized energy levels. Specific examples include electronic, magnetic or vibrational states of superconducting or spin qubits, neutral atoms, [neutrons] or trapped ions.
2. Use of quantum **coherence** (i.e., wavelike spatial or temporal superposition states) to measure a physical quantity. **Quantum 1.0**
3. Use of quantum **entanglement** to improve the sensitivity or precision of a measurement, beyond what is possible classically. **Quantum 2.0**

<https://doi.org/10.1103/RevModPhys.89.035002>



U.S.A.F. Scientific Advisory Board, *Utility of Quantum Systems for the Air Force*, 2015.

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# Potential application impact



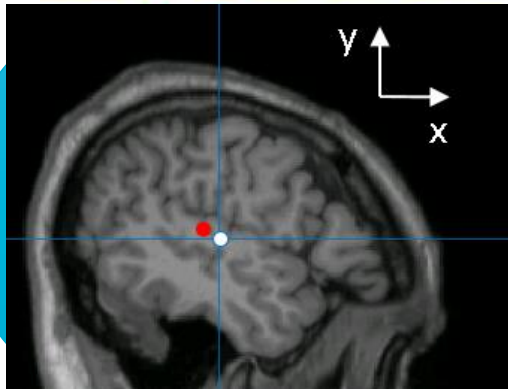
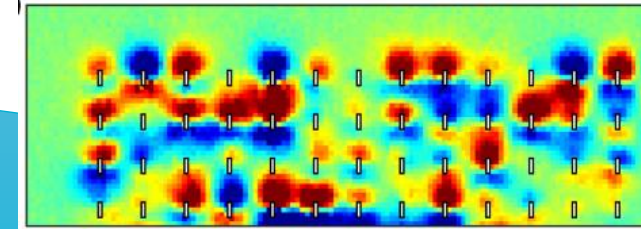
Timing



Non Destructive Evaluation



Magnetic mapping

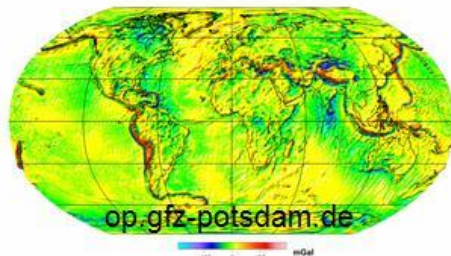


Medical Imaging

QUANTUM  
SENSORS



Navigation



Gravimetry



Communications



Trace Chemical  
Detection

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- March 2022 report: Bringing Quantum Sensors to Fruition

**Box 7: Recommendations to Facilitate the Development and Utilization of Quantum Sensors**

- 1. Agencies leading QIST R&D should accelerate the development of new quantum sensing approaches and prioritize appropriate partnerships with end users to elevate the technology readiness of new quantum sensors.**
- 2. Agencies that use sensors should conduct feasibility studies and jointly test quantum prototypes with QIST R&D leaders to identify promising technologies and to focus on quantum sensors that address their agency mission.**
- 3. Agencies that support engineering R&D should develop broadly applicable components and subsystems, such as compact reliable lasers and integrated optics, to facilitate the development of quantum technologies and promote economies of scale.**
- 4. Agencies should streamline technology transfer and acquisition practices to encourage the development and early adoption of quantum sensor technologies.**

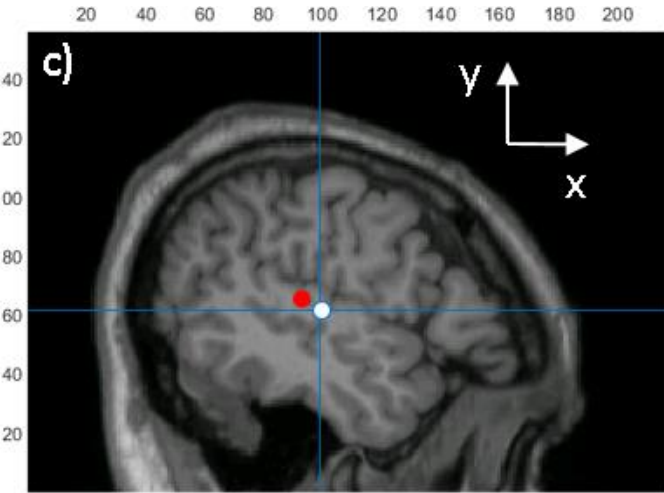
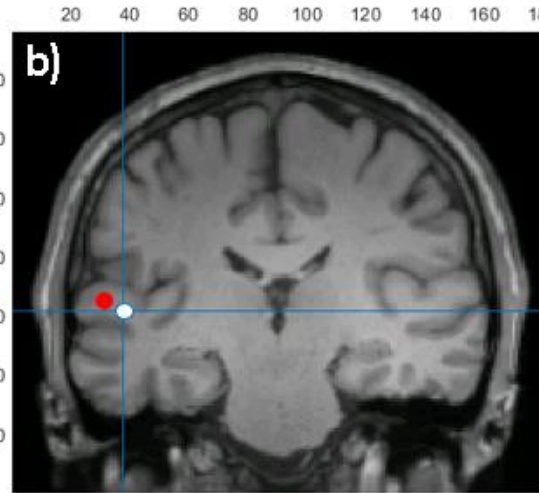
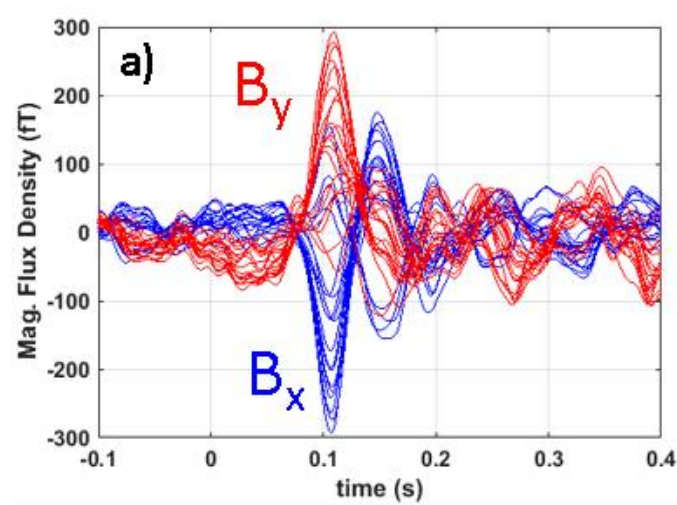
# Optically pumped magnetometers (OPMs) at Sandia



- OPMs for magnetoencephalography (MEG)
  - National Institutes of Health
- OPMs for the detection of signatures from capacitive discharges units (CDUs)
  - National Nuclear Security Administration (NNSA):NA-22
- Development of a OPM gradiometer
  - DARPA:Atomic Magnetometer for Biological Imaging In Earth's Native Terrain (AMBIENT)
- RF OPM for Low Frequency (10 kHz to 500 kHz) detection
  - Internally funded: LDRD
- Nitrogen-vacancy centers in diamond
  - Internally funded: LDRD
  - High spatial resolution magnetometry
    - Electrical circuit failure analysis



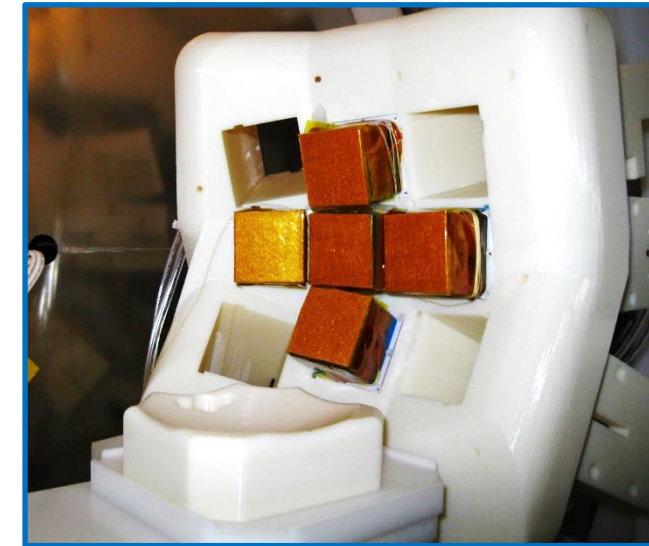
# Magnetoencephalography (MEG): localize auditory activity



Magnetic Shield

5-sensor, 20-channel array

- Auditory stimulation
  - 1000 Hz tone, every 1 to 1.5 s
  - 456 trials
- White dot: OPM location
- Red dot: SQUID MEG location
- Sandia expertise with MEG can be applied to underground utility mapping



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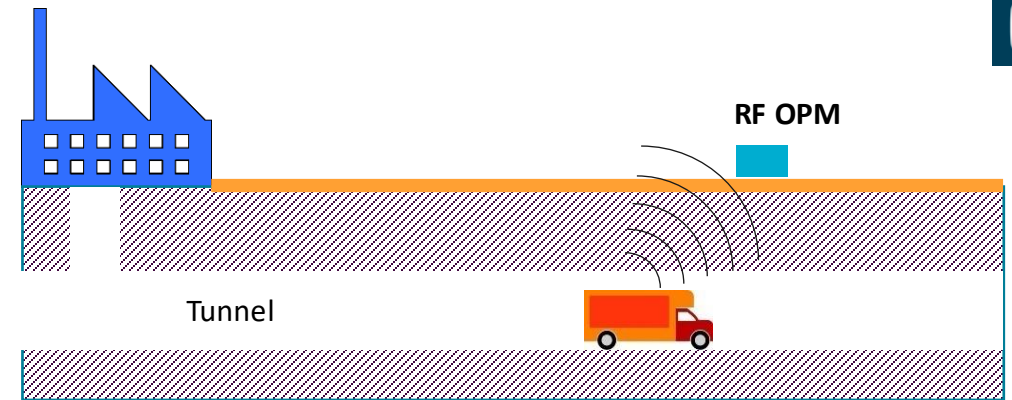
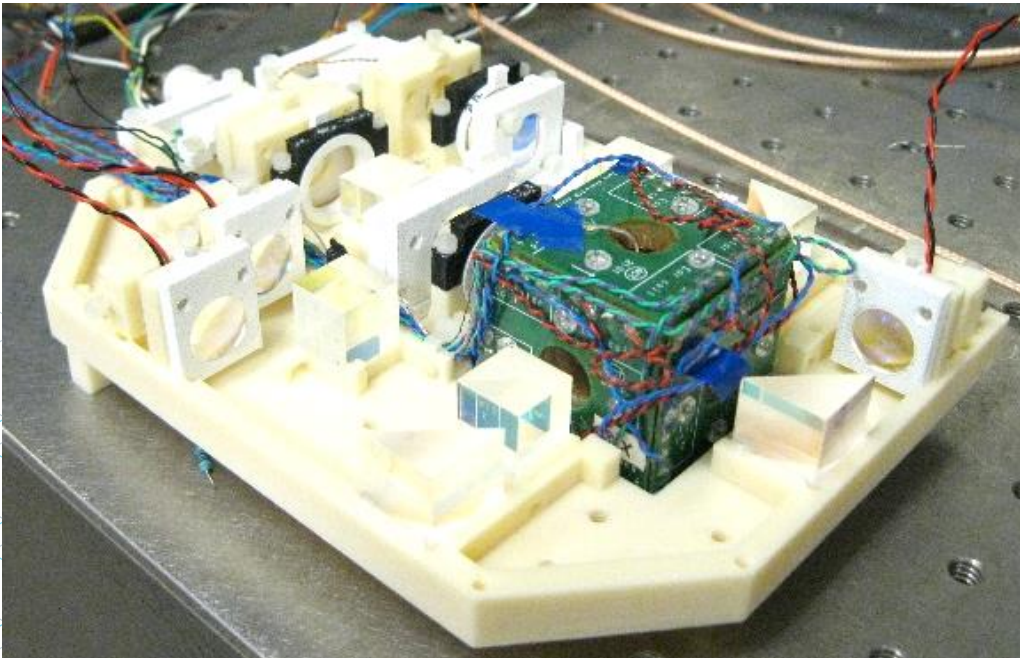


# RF magnetometer

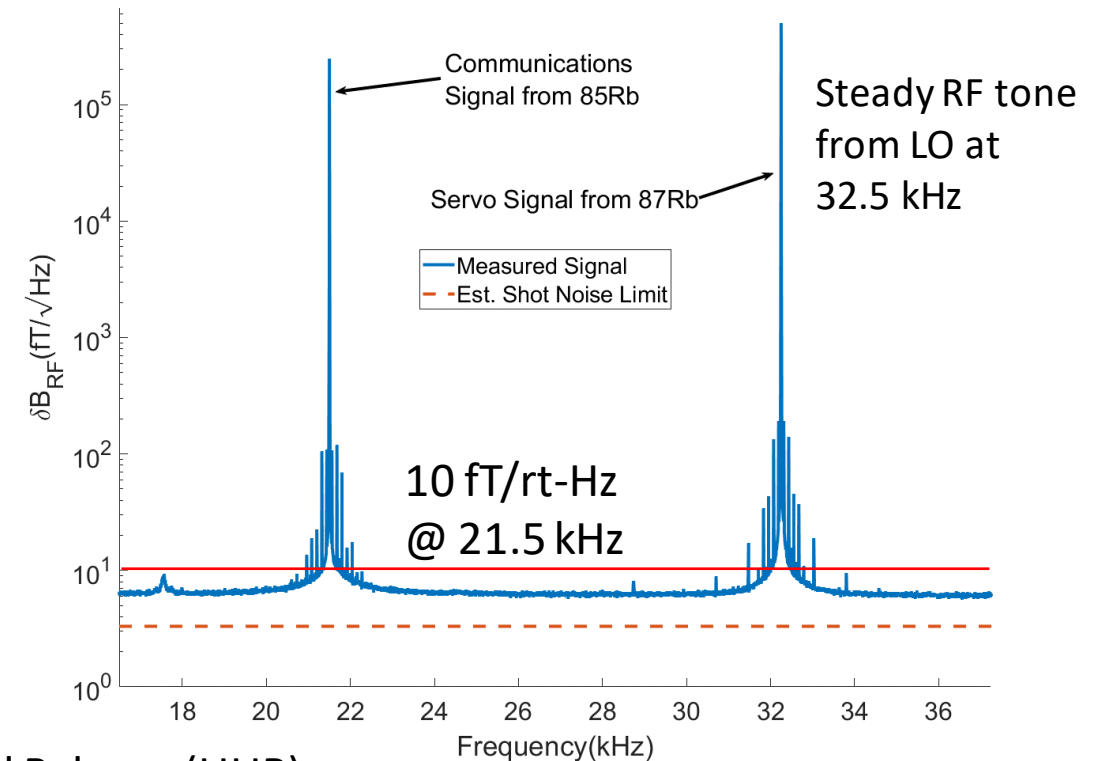
- Quantum sensor suitable for signal transmission through soil and utility detection
- VLF (3-30 kHz) can penetrate buildings, soil, water
- Compact sensor head: 0.6 L
- Unshielded operation: active feedback to lock onto desired frequency

J. Dhombridge et al., submitted to PRA (2022).

Miniaturized sensor head



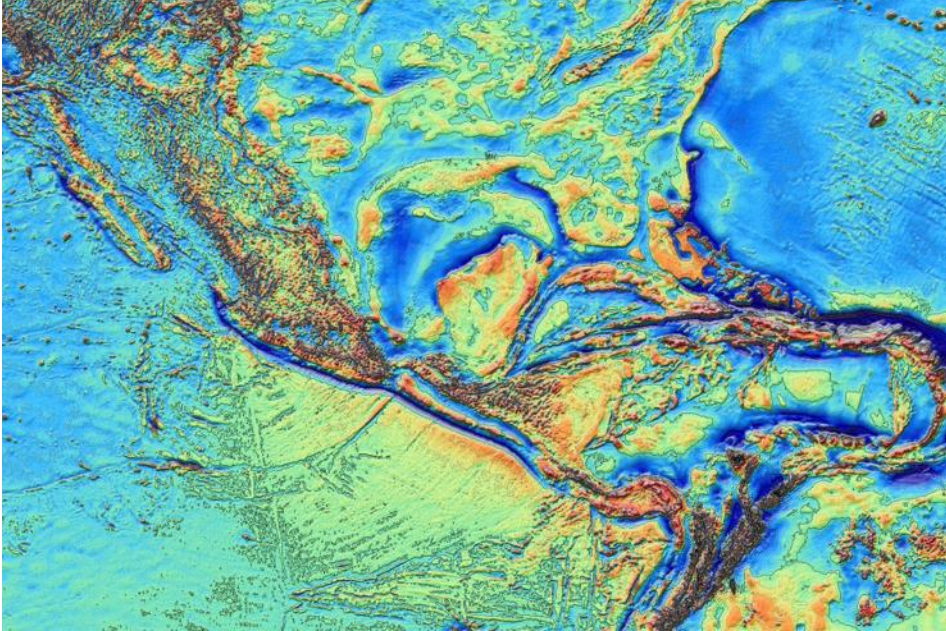
Sensor performance vs. frequency



# Gravity anomaly mapping with quantum gravimeter

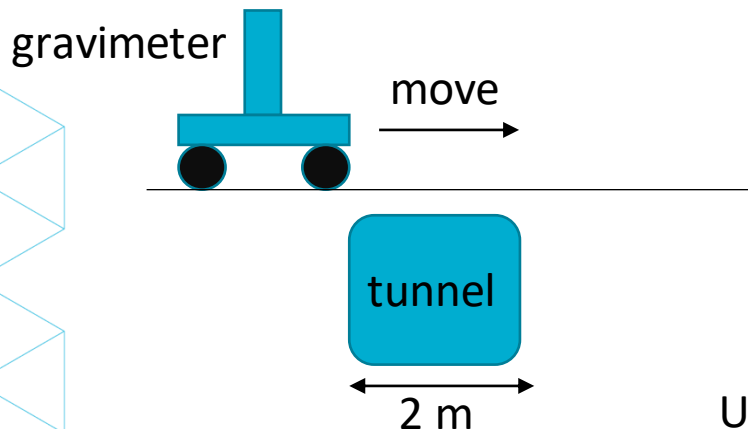


Combined Gravity Anomaly (North America)



Sandwell et al., Science, 346, 6205 (2014).

- Gravity anomalies due to mass variations underground can be detected by sensitive gravimeter (accelerometer)
  - Cannot be shielded
  - Less sensitive to clutter than mag
- Techniques pioneered by oil & gas industry for large scale resource exploration
- Current quantum gravimeters are large
  - 7 kg weight, 13 L volume
  - Suitable for topside mapping
  - Further miniaturization/ruggedization needed!
- Mass anomaly modeling capability exists at SNL-CA
  - Can apply to utility detection problem
  - Few cm resolution desirable
  - 50 cm spatial resolution demonstrated in tunnel detection (Stray et al., Nature, 602, 590 (2021)).

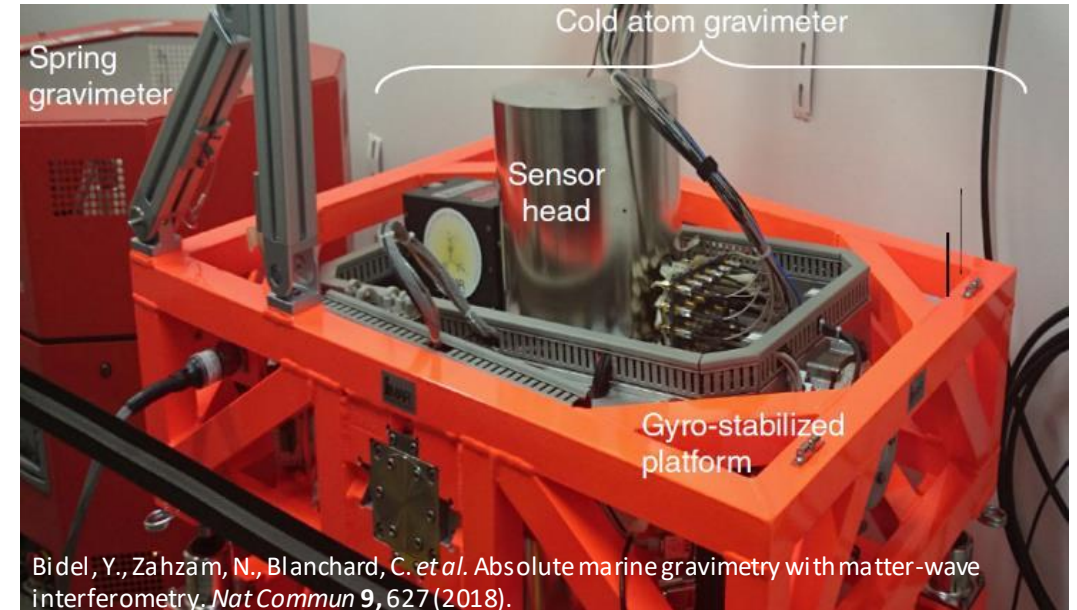


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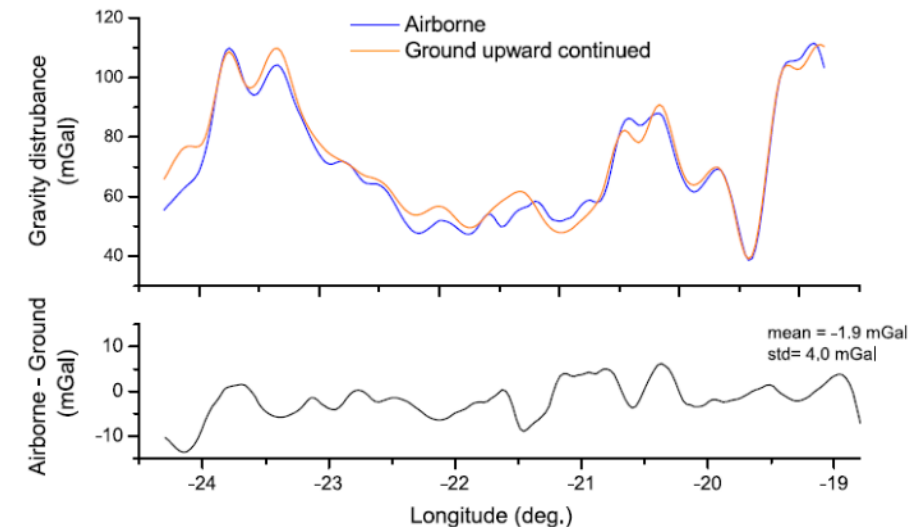
# Airborne gravimetry with atom interferometer



- Gravity measurements over Iceland
- Gimballed platform to maintain vertical
- Feed forward technique
  - Dynamic range = 1000 fringes or  $\sim 0.1$  g at  $T = 20$  ms
- Data rate = 10 Hz
- Errors: 1.7 to 3.9  $\mu\text{g}$
- ONERA – The French Aerospace Lab



Bidel, Y., Zahzam, N., Blanchard, C. *et al.* Absolute marine gravimetry with matter-wave interferometry. *Nat Commun* 9, 627 (2018).



**Aircraft:** Bidel, Y., Zahzam, N., Bresson, A. *et al.* Absolute airborne gravimetry with a cold atom sensor. *J Geod* **94**, 20 (2020).

**Ship:** Bidel, Y., Zahzam, N., Blanchard, C. *et al.* Absolute marine gravimetry with matter-wave interferometry. *Nat Commun* **9**, 627 (2018).



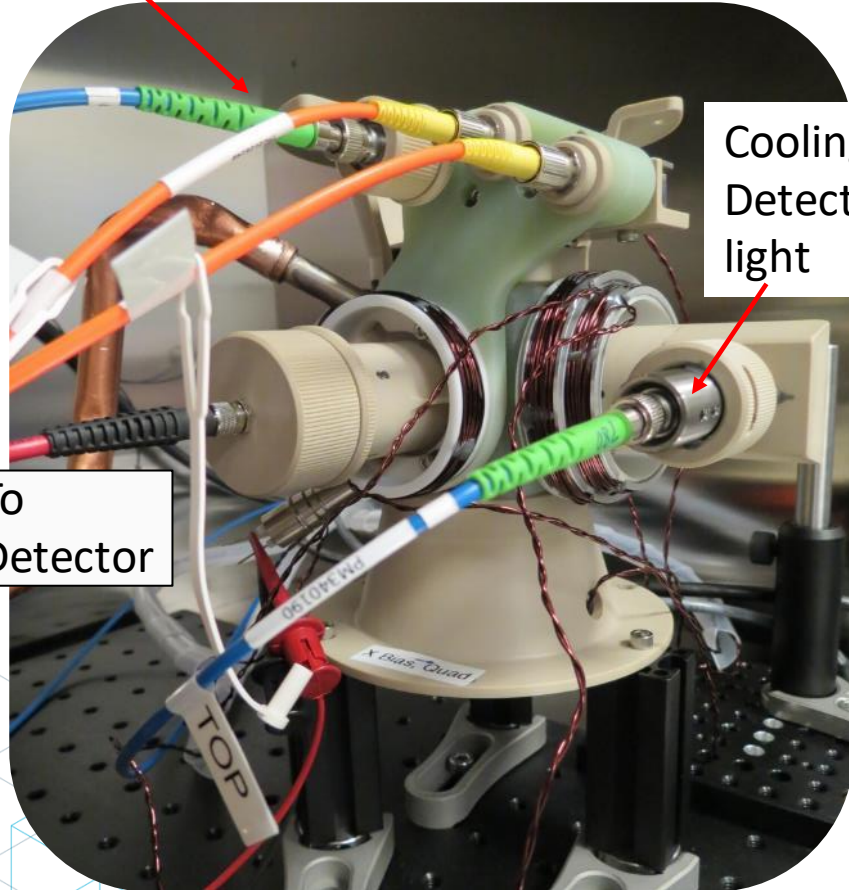
# Sandia compact atom interferometer sensor head



Raman light

Cooling/  
Detection  
light

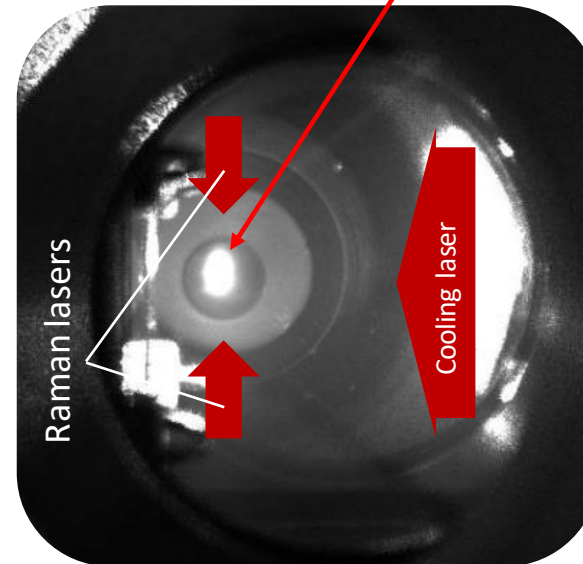
To  
Detector



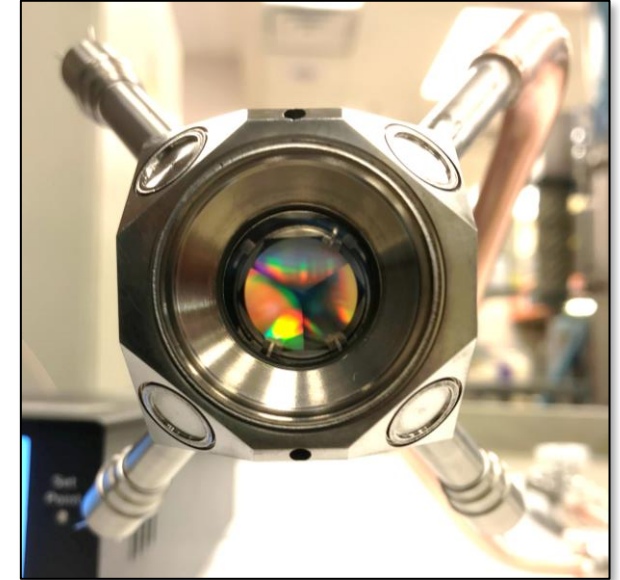
Same Raman configuration used in  
McGuinness, et al., APL (2012)

- Grating magneto optical trap (GMOT)
- Grating replaces one window of vacuum package
- Vacuum maintained by ion pump, fused silica windows
- Atom number:  $10^7$   
laser cooled to  $18 \mu\text{K}$ .

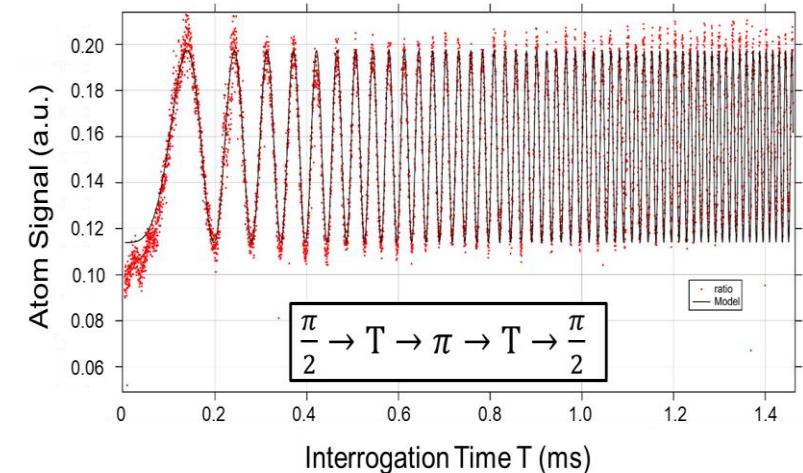
GMOT



Ti Vacuum Package with Grating



Gravimeter Signal



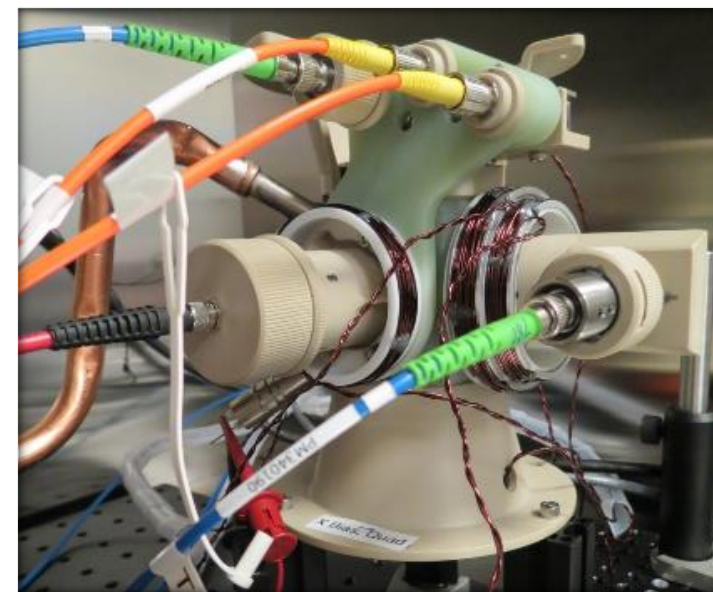
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# Inertial sensing with atom interferometry

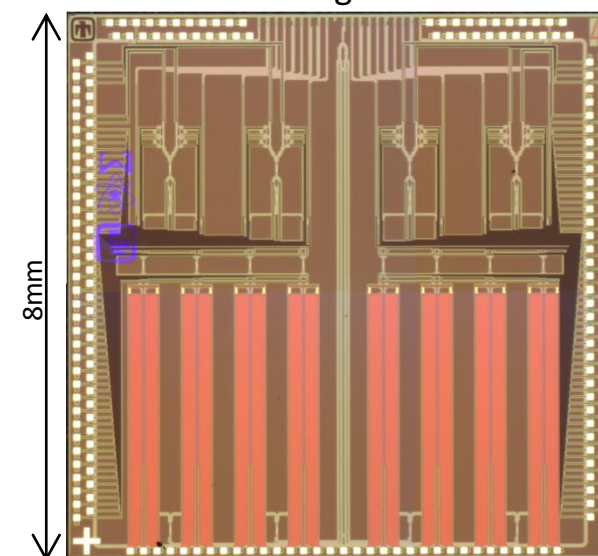


- Strategic-grade accelerometer:  $0.25 \mu g$
- 50 Hz data rate
- Targeting a fieldable sensor
- Developing chip-scale laser system (PIC) for extreme miniaturization



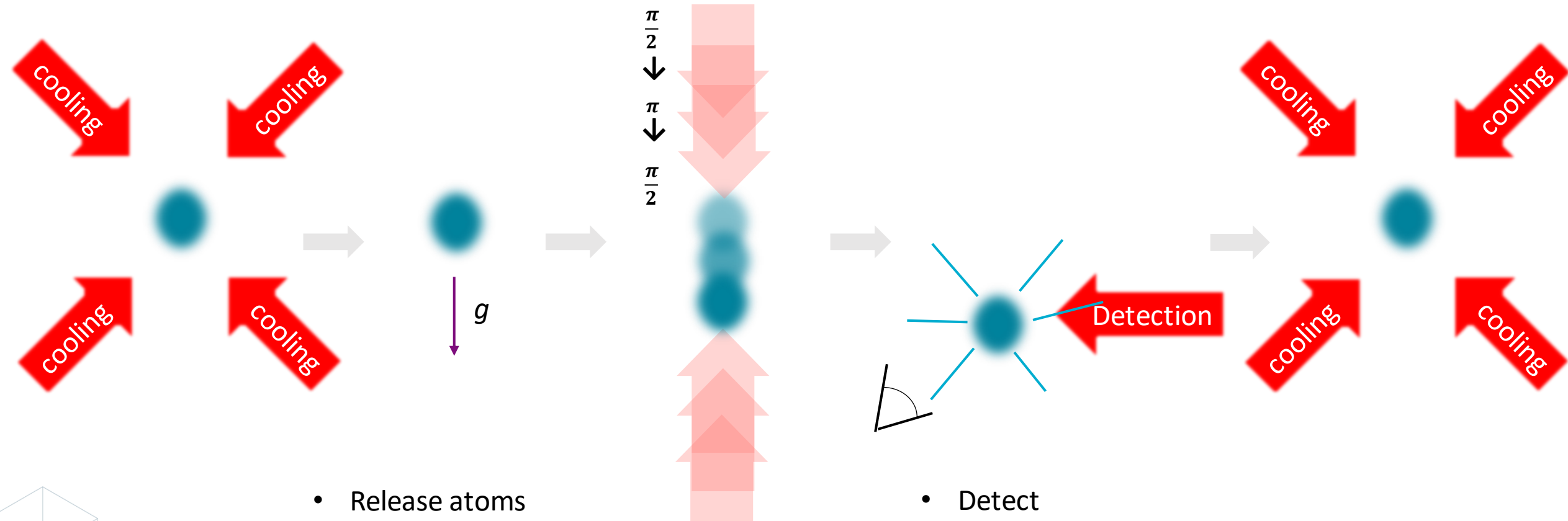
GMOT Grating

Photonic Integrated Circuits



Unclassified Unlimited Release (UUR)

# High data rate atom interferometry



- Laser cooled atoms (4.3 ms,  $T \approx 15 \mu\text{K}$ ,  $N \approx 10^6$ )

- Raman pulse sequence (14 ms,  $T = 7 \text{ ms}$ )  
 $\frac{\pi}{2} \rightarrow T \rightarrow \pi \rightarrow T \rightarrow \frac{\pi}{2}$

- Recapture (1.7 ms)

*Example,  $(40 \text{ Hz})^{-1}$  cycle = measure acceleration every 25 ms*

H. J. McGuinness, et al.,  
 Appl Phys Lett **100**, 011106 (2012).

Unclassified Unlimited Release (UUR)